A META-ANALYSIS OF HOW MANAGEMENT PRACTICES AFFECT SOYBEAN YIELD AND QUALITY

BY

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THESIS

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ABSTRACT

Soybean [*Glycine max* (L.) Merr.] is a major cultivated crop, providing protein and oil for human and animal feed. While soybean yields in the United States have increased over the years, grain oil concentrations have remained relatively constant while protein concentrations have decreased. The objective of this work was to determine if management practices (nitrogen (N), phosphorus (P), and potassium (K)) fertilization; foliar protection, and reduced row spacing) could simultaneously increase yield as well as seed protein and oil concentrations. A meta-analysis was performed on 50 soybean crop management projects conducted between 2012 and 2018, which included five field sites around Illinois. These trials measured yield, seed protein and oil concentrations, weather (precipitation and temperature), soil constituents (CEC, organic matter, P and K levels), and recorded planting and harvest dates. A meta-analysis of the mean differences was used to examine the impact of management practices on yield, and moderators to explain the heterogeneity levels between studies were included. Nitrogen or P fertilization, reduced row spacing and foliar protection all increased yield, while K fertilization tended to decrease yield. Seed protein concentration was not affected by N or K fertilization, but was altered by P fertilization depending on the method of application. Seed protein concentration decreased when the P fertilizer was banded beneath the crop row, but tended to increase when the P fertilizer was broadcasted on the soil surface. Reduced row spacing and foliar protection decreased seed protein concentration. Banded P fertilization, reduced row spacing, and foliar protection all increased seed oil concentration. Soil organic matter level and planting date were moderators that explained the variation in the responses to N fertilization of soybean yield and protein concentration, respectively. In regards to P fertilization, soil P level was a moderator of the yield response, while soil CEC was a moderator of the seed oil concentration response. Yield and seed quality responses

to reduced row spacing were both moderated by soil CEC. In response to foliar protection, yield was moderated by soil organic matter, while seed protein and oil concentrations both had location as a moderator. These data show that N and P fertilization, reduced row spacing, and foliar protection can individually increase soybean yield, and that banded P fertilization, reduced row spacing and foliar protection can increase seed oil concentration, but no management practice evaluated in this review was able to simultaneously increase yield and seed protein concentration.

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INTRODUCTION

Soybean (*Glycine max* [L.] Merr.) is a leguminous plant, in the biological family *Fabaceae (Leguminosae)*. Its center of origin is in the northwest of China, specifically the Manchuria region (EMBRAPA, 2005; Missao, 2006), where domestication of soybean started three millenniums ago (North Carolina Soybeans Producers Association, 2019). The ancient cultivated soybean had a creeping growth habit and grew along wetlands near lakes and rivers (Aprosoja, 2014). Through breeding, the Chinese started its cultivation before English travelers and oriental immigrants (Missao, 2006) dispersed it to the south of China, as well as to Korea and to Japan in the 3rd century B. C. (Aprosoja, 2014).

In the United States, a Georgia British colonist introduced soybean in 1765, but cultivation expanded greatly eighty-six years later, with the distribution of seeds to farmers in Illinois and other states in the Corn Belt (North Carolina Soybeans Producers Association, 2019). Soybean became a commodity worldwide in 1919, after the First World War, and its world production chain was established with the creation of the American Soybean Association (Aprosoja, 2014).

Currently, soybean is a major globally-cultivated crop, with worldwide production increasing every year. Soybean cultivation reached 352.6 million metric tons in 2017, representing an increase of 5.1% in relation to 2016 (FAO, 2019). Consequently, the consumption of soybean around the world increased 4.54% from 1987 to 2009 (Lazzarotto and Hirakuri, 2010). One reason for this historic increase in soybean production in the world is the various uses for its grain, especially its protein and oil, which are components of high economic importance (Brumm and Hurburgh, 1990; Hurburgh, 1994). The United States is one of the main producers of soybean worldwide, producing 120.52 million metric tons in the 2018/19 season, or 33.6% of the world total (USDA-FAS, 2019). Of the U.S. production in 2018 that was not exported, 47.4% was crushed (USDA-NASS, 2019), a process that creates two co-products: meal and oil.

Soybean meal is one of the major protein sources for animal feed, due to its balanced amino acid profile and high digestibility level, making it universally accepted as the most important protein ingredient in animal diets (Willis, 2003). Compared to other animal-feed protein sources, soybean has the highest quality, providing an economic advantage to its use (Grieshop and Fahey, 2001). The United States production of soybean meal was 44,626 metric tons in 2017/18 and has been increasing since 2015 (USDA-NASS, 2019). The marketing of soybean meal is highly dependent on its protein concentration meeting a required minimum (Rotundo et al., 2016) following oil extraction from the crushed grain (Brumm and Hurburgh, 1990). The desired concentrations of protein and lipids in the soybean grain are 400 g kg^{-1} and 200 g kg^{-1} of the dry matter, respectively (De Moraes et al., 2006), which is equivalent to 348 and 174 g kg^{-1} of the grain at 130 g kg^{-1} moisture. Since the beginning of the 21st century, soybean grain protein concentration has been decreasing. Protein concentration also has been lower than the desired concentration since 2012, when the reported levels at 130 g kg^{-1} moisture were 343 g kg^{-1} for protein and 185 g kg^{-1} for oil (Miller-Garvin and Naeve, 2017). The productivity of American soybeans has been increasing annually, achieving yield of 3331 kg ha^{-1} in 2017 (Miller-Garvin and Naeve, 2017). However, because the protein concentration in the grain has been decreasing, the concentration in its meal coproduct has simultaneously been tending to decrease. Therefore, to supply the same amount of protein, more of the less-protein concentrated meal is needed, which increases feed costs and influences the final price of the resulting animal meat (Plume, 2017). The lower protein concentration in the grain also hiders the United States exports of soybean, resulting in lost market share in China to other countries that have a higher level of grain protein (Plume, 2018).

The other coproduct of the crushed grain, soybean oil, also is directly related to its concentration in the original soybean grain. Similar to meal, its production has increased and reached approximately 10.8 million metric tons in 2017/18 (USDA-NASS, 2019). Besides direct human nutrition as a food additive, the process to obtain oil generates lecithin, which is a versatile coproduct. Lecithin is used as an emulsifying agent in the food industry (Hymowitz and Newell, 1981), but it is also used in the production of paints, insecticides, cosmetics and textiles (Scott and Aldrich, 1970; Wolf and Cowen, 1971). Recently, transesterification technology has allowed soybean oil to be used as biodiesel (Kinney and Clemente, 2005). According to Kinney and Clemente (2005, p. 1139), "approximately 3.6% of the U.S. soybean oil production is targeted for industrial applications (approximately 288 million kg), of which 1% (4.5 million kg) is used for biodiesel". Thus, a continued increase in demand for soybean oil is expected to occur. Historically, soybean grain oil concentration has been increasing concurrently with the yield increase (Miller-Garvin and Naeve, 2017). However, since 2010, the production of the oil has been less than the demand (USDA-ERS, 2019). In 2017/18, the gap in the production of soybean oil compared to the amount used was less than the previous season, decreasing from –133,734 to -23,122 metric tons (USDA-ERS, 2019), with processing of stored grain helping to overcome the shortfall. With the potential for further increased use of soybean oil by industry, there is a need to continue increasing the soybean grain oil concentration concurrently with yield.

The final soybean grain quality (protein and oil concentrations), similar to yield, is driven by a combination of the seed genetics, the growing environment, the agronomic management practices, and their interactions (De Bruin and Pedersen, 2008; Assefa et al., 2019). Some of the soybean agronomic management practices available include the location, genetics, nutrient fertilization, planting row configuration, and foliar protection. Since the mid-1990s, the U. S. Soybean Board has led an initiative to increase the compositional quality of the U. S. soybean to meet the domestic market need through identifying and improving the associated traits (Durham, 2003). However, the influence of each factor on the resulting grain quality characteristics is not entirely known (Rao et al., 2002; Assefa et al., 2018).

Several studies reported the influence of the plant growth environment on the resulting soybean grain quality (Grieshop et al., 2003; Rotundo et al., 2016; Mourtzinis et al., 2018; Assefa et al., 2018, 2019). The consensus among these studies is that soybeans cultivated in warmer areas, with adequate water throughout the season tended to have higher concentrations of both protein and oil in the grain. This greater compositional grain quality may be linked to the center of origin of the crop, which has humid summers with tropical heat (Box and Choi, 2003). Thus, expanding soybean cultivation to areas in the country that are colder and/or have water limitations during the growing season impacts the average quality of U. S. soybeans.

In addition, Assefa et al. (2019) relate planting date with the environment for plant growth, because it determines the time that the crop will be exposed to the environment and the period that the nutrients are available to the plant. In the same study, the response to planting date was also linked to latitude, in which soybean planted after the 145th day of the year tended to have less yield and grain oil concentration than those planted earlier when grown in the mid to high latitude ranges in the United States (35-45° N).

Different ranges in temperature also could be reflected in high yield variability as well as in the amino acid profile of the soybean grain (Carrera et al., 2011). In addition, soil characteristics could influence the growth of soybean, such as cation exchange capacity (CEC) and organic matter. Villamil et al. (2012) studied soybean yield from on-farm data in Illinois and found that soil CEC and organic matter levels had a negative relationship with grain yield.

Modern techniques have increased the efficiency of the breeding process, optimizing variety development by private institutions, consequently introducing more varieties with higher yield potential (Sleper and Shannon, 2003). Genetic traits linked to high protein grain have been identified (Wilcox and Cavins, 1995; Cober and Voldeng, 2000; Sebolt et al., 2000). However, current breeding programs have focused primarily on yield potential, while the grain quality became a secondary factor of minimal interest. Thus, one approach to achieving greater grain quality is for companies to develop new high-yielding varieties that also generate high grain quality in the multitude of production environments available.

Even with modern breeding techniques, new varieties take a significant amount of time to be launched into the market. Therefore, another solution to the low-quality profile of the grain could be done with in-season management of the current existing varieties. Modern soybean systems are focused on high yields, which are linked to rapid canopy closure, comprised of more leaves and more photosynthetic tissue (Arce et al., 2009). These soybean systems must have sufficient nitrogen to assist in the conversion of solar radiation into new biomass and grain yield (Salvagiotti et al., 2008).

Nitrogen is one of the most required elements by plants and it is a component of proteins (Souza and Fernandes, 2006). Soybean can use many forms of nitrogen, including atmospheric nitrogen because of its symbiotic relationship with *Bradyrhizobium japonicum* bacteria (Macák and Candráková, 2013). The peak nitrogen fixation rate occurs in the late plant reproductive stages (Zapata et al., 1987). Demand prior to that peak needs to be supplied by another nitrogen source (Salvagiotti et al., 2008) to avoid remobilization from other tissues, which could limit yield (Kessel and Hartley, 2000). Therefore, external provision of this nutrient could be a viable alternative for a system focused on the combination of higher yields and quality.

Besides nitrogen, phosphorus is necessary in many processes of plant metabolism, such as energy transfer, synthesis of nucleic acids, and cellular membrane stability (Araujo and Machado, 2006), and also helps in the fixation of atmospheric nitrogen (Vance et al., 2003). In addition, Bender (2015) found that 80% of the accumulated phosphorus from a modern soybean plant is removed with the grain, and if not replenished in the soil, may result in future yield limitations. Farmaha et al. (2012) observed significant effects of phosphorus fertilization on soybean protein and oil concentrations and yield under different tillage systems. Phosphorus fertilization was able to increase protein and oil in the grain when applied before sowing in a study performed in Pakistan (Abbasi et al., 2012). In the same study, potassium fertilization was able to increase yield and quality of soybean grain at both supply levels, 40 and 80 kg ha^{-1}. In addition, in the United States, soybeans are commonly fertilized with potassium at a higher rate than any other nutrient because of the perception among growers that it is the most important nutrient to soybean (USDA-ERS, 2017).

Besides nutrient fertilization, other agronomic management procedures could be done to enhance yield and quality of the soybean crop. Reducing row spacing is a valuable practice that is associated with earlier canopy closure (Ball et al., 2000; Silva et al., 2013; Andrade et al., 2019). Reducing row spacing also permits more light interception (Çalişkan et al., 2007; Zhou et al., 2011; Silva et al., 2013) and is associated with an increase the leaf area index per plant (Zhou et al., 2011; Malek et al., 2012), which can lead to more yield at the end of the season. However, it has been reported that reducing the row spacing less than 30 cm did not result in a yield increase (Moreira et al., 2015; Ferreira et al., 2019), suggesting that there might be minimum row spacing threshold for optimum soybean growth and yield. Regarding grain quality, narrowing the row spacing has led to mixed results, ranging from not affecting it (Al-Tawaha and Seguin, 2006; Bellaloui et al., 2014; Flajšman et al., 2019) to increasing the quality (Moreira et al., 2015; Werner et al., 2017).

The plant canopy is mainly composed of leaves, which have photosynthesis as their major function (Taiz and Zeiger, 2010). Thus, protecting the integrity of leaves from foliar diseases and feeding from insects using fungicidal and/or insecticidal products is a viable practice to increase soybean yield. Yield gains from applications of those products have been found, especially when disease pressure was high for a specific pathogen (Delaney et al., 2018; Molina et al., 2019; Willbur et al., 2019). Other studies have shown a yield benefit of these products regardless of the disease pressure presumably due to growth regulator effect (Bender, 2015; Beyrer, 2018). However, foliar applications are not a guarantee of higher yields (Swoboda and Pedersen, 2009). Assefa et al. (2019) reported that fungicide and insecticide applications resulted in increased grain oil concentration and had a tendency to increase soybean grain protein level. Therefore, the management practice of foliar protection could be a viable strategy towards increased soybean yield and quality. However, a better understanding of the use of foliar protectants is needed, since fungicide alone has been found to be as effective as a mixture with an insecticide (Ng et al., 2018).

Management practices on soybean production have been widely studied. Thus, summarizing the findings of an array of studies regarding the effect of management practices on yield and grain quality could be a comprehensive way to evaluate overall management effect. Meta-analysis is a statistical tool used to synthetize and quantify the evidence present in many studies for a certain treatment. It became popular in 1980's in medicine and social sciences as an alternative to narrative reviews (Borenstein et al., 2009a; Hedges and Olkin, 2014). It was introduced to other fields such as ecology and biology in the early 1990's (Jarvinen, 1991;

Gurevitch et al., 1992) and started being used in agronomy in the early 2000's (Marra and Kaval, 2000; Ainsworth et al., 2002; Miguez and Bollero, 2005). Similarly to an analysis of variance, an overall effect of the treatment is reported, which results from a weighted mathematical calculation of all the studies included in the meta-analysis, providing an objective, clear and replicable result (Borenstein et al., 2009a).

In agronomy, it is known that each study is different because it is performed in a specific year and location, thus, variance between studies is expected, and the usage of the random-model effects in agronomic meta-analysis is preferred because it accounts for and quantifies that variability (Borenstein et al., 2009b; Mengersen et al., 2013), also known as heterogeneity (I^2). In areas that are expected to have variability among studies, quantifying that variability and explaining it is crucial for a complete meta-analysis (Koricheva et al., 2013). Dividing the data into sub-groups and/or including moderators (similar to an analysis of covariance) that quantifies the differences between studies could explain the heterogeneity (Borenstein et al., 2009a; Steward et al., 2013). However, minimizing the number of moderators is a good way not to over fit the model and introduce bias (Steward et al., 2013).

The moderator or subgroup could be statistically relevant or not, depending on its probability value (p-value). For moderators, other statistical values could be of importance to assess the most relevant moderator when the p-value among them are similar. The Akaike information criteria (AIC) is informative when comparing different models (with different moderators) indicating the best model among others as the one that minimizes the AIC value (Sakamoto et al., 1988). Also, since moderators are included in a regression model, regression estimators, such as R^2 could also be used, and in the case of meta-regression it means the amount of the original heterogeneity present in the model that came from between-study variance (I^2) that could be explained when the moderator was added to the model (Viechtbauer, 2010).

In summary, taking into consideration that modern soybean varieties have a greater focus on yield potential and that soybean cultivation is moving to colder areas in the United States and Canada, the protein level of United States soybean is decreasing each year. The lower quality impedes both animal production, since soybean meal is an important source of protein for animal feed, and the international trade of the commodity, since other countries could offer a higher quality soybean for similar prices.

Developing new varieties to overcome the issue of low grain protein concentration could be a solution, but that path must make financial sense for the breeding companies. A more viable alternative is to manage soybeans during the season not only for yield, but also for the grain quality aspect. Research needs to be done with the primary intention of determining how agronomic management affects yield and grain quality.

Therefore, the objectives of this study were to determine if agronomic management practice(s) could simultaneously increase soybean yield and grain quality, and if so, which practice(s) would be the most influential in altering yield and quality characteristics. To accomplish the objectives, meta-analytic methods were used on data archived from studies of the Crop Physiology Laboratory of the University of Illinois.

METHODS

The Crop Physiology Laboratory has a vast database of soybean experiments from 2012 to 2018, using five locations in the state of Illinois: DeKalb (41°55′53″N 88°45′01″W, 268 m above sea level); Yorkville (41°39′57″N 88°26′31″W, 200 m above sea level); Champaign (40°06′54″N 88°16′22″W, 233 m above sea level); Rushville (40°07′16″N 90°33′47″W, 205 m above sea level); and Harrisburg (37°44′02″N 88°32′45″W, 121 m above sea level). All experiments consisted of replicated treatments arranged in randomized complete block design and measured for yield (metric tons (T) hectare^{-1} with 0 g kg^{-1} moisture concentration), harvested with and Almaco™ plot harvester, and a sample was analyzed using a NIR transmittance analyzer (Infratec 1241; FOSS, Denmark) to obtain grain protein and oil concentrations (g kg^{-1}) standardized to a moisture concentration of 130 g kg^{-1}. Additional information collected for all trials included: planting and harvest dates; average temperature (Celsius) and total precipitation (mm); soil cation exchange capacity (CEC) (Meq 100 g^{-1}); organic matter (OM) (g kg^{-1}); pH; and preplant soil phosphorus and potassium levels (mg kg^{-1}) The experiments all had accurate records of their protocols, with treatment descriptions, number of replications and soybean variety(ies) used. The collected results were stored in a main database each year making the data easily retrievable.

Selection of experiments

For this study, the seven years of experiments up to and including 2018 were considered, encompassing 70 experiments. Soybean studies with at least three replications each were selected that had evaluated at least one of the following management practices: dry fertilizer applications, fungicide and/or insecticide application, and/or row spacing. Ultimately, six experiments were selected that spanned 50 site-year combinations: “Soybean Management Yield Potential”;

“Soybean Omission Plots”; “Phosphorus Source, Rate and Placement Soybean”; “Soybean Response to Nitrogen”; “Soybean Fertigation”; and “Soybean Relay”. These experiments are briefly explained below and the locations, agronomic management(s), and data used are summarized in Appendix A.

Soybean Management Yield Potential

The Soybean Management Yield Potential experiment was performed from 2016 through 2018. It was planted at three locations in Illinois (Yorkville, Champaign and Harrisburg), resulting in eight site-years. The goal of this trial was to categorize different soybean varieties regarding of their yield response to phosphorus fertilization and foliar protection. A resulting offensive variety would be one that increases yield with both inputs compared to a defensive variety as one that would have a stable yield regardless of the inputs. A split-plot randomized complete block design with four replicates was used with the whole plot being fertility and the split plot being foliar protection, with the randomization restricted to the thirty different varieties tested every year. Phosphorus (P) fertilization, banded directly underneath the crop row before planting, at a rate of 84 kg ha^{-1} of phosphorus was provided by the products MicroEssentials SZ™ (MESZ) (12-40-0-10S-1Zn) (Mosaic, Minneapolis, MN) in 2016 but was substituted with MicroEssentials S10™ (MES10) (12-40-0-10S) (Mosaic, Minneapolis, MN) in the 2017 and 2018 trials. Foliar applications of fungicide at the R3 growth stage were accomplished using Quadris Top® SB™ (Azoxystrobin + Difenoconazole; Syngenta, Greensboro, NC) at 874 ml ha^{-1} for 2016, and for 2017 and 2018 Trivapro™ (Benzovindiflupyr +Azoxystrobin + Propiconazole at 1000 ml ha^{-1}; Syngenta, Greensboro, NC) was used. The insecticide was applied at R3 with or without the fungicide Endigo® ZC™ (Lambda-cyhalothrin + Thiamethoxam at 292 ml ha^{-1} (Syngenta, Greensboro, NC) for the respective treatments all three years.

Soybean Omission Plots

Conducted from 2012 to 2018 at five locations in Illinois (DeKalb, Yorkville, Rushville, Champaign and Harrisburg), this experiment totaled 19 site-years. Multiple agronomic practices were investigated as part of this study, including row spacing, fertilization with phosphorus and/or potassium before planting, and foliar protection with fungicides and/or insecticides at the R3 growth stages. In years that had multiple inputs with a similar mode of action, treatments were combined for data analysis, theoretically increasing the statistical power. This experiment was conducted as a split-plot RCBD, with row spacing as the main block and replication as the split plot. Brief details of the major agronomic managements evaluated each year are as follows:

2012 and 2013 - Phosphorus fertilization: MESZ to provide 84 kg of P_2O_5 ha^{-1}, banded before planting. Foliar protection: Fungicide (Quilt Xcel™ at 1,022 ml ha^{-1} and Priaxor™ at 292 ml ha^{-1}) and insecticide (Endigo ZC™ at 292 ml ha^{-1} and Fastac™ at 278 ml ha^{-1} [Alpha-cypermethrin; Florham Park, NJ]) applied at plant growth stage R3 either individually or combined. Reduced row spacing: 50.8 cm compared to 76.2 cm.

2014 - Phosphorus fertilization: MESZ to provide 84 kg of P_2O_5 ha^{-1}, banded before planting. Potassium fertilization: Aspire™ (0-0-58-0.5B) (Mosaic, Minneapolis, MN) to provide 84 kg of K_2O ha^{-1}, broadcasted before planting. Foliar protection: Fungicide (Priaxor™ at 292 ml ha^{-1}) and insecticide (Endigo ZC™ at 292 ml ha^{-1} and Fastac™ at 278 ml ha^{-1}) applied at R3 either individually or combined. Reduced row spacing: 50.8 cm compared to 76.2 cm.

2015 - Phosphorus fertilization: MESZ to provide 84 kg of P_2O_5 ha^{-1}, banded before planting. Potassium fertilization: Aspire™ to provide 84 kg of K_2O ha^{-1}, broadcasted before planting. Foliar protection: Fungicide (Priaxor™ at 292 ml ha^{-1} and Quadris Flowable™ at 438 ml ha^{-1} [Azoxystrobin; Syngenta, Greensboro, NC]), insecticide (Endigo ZC™ at 292 ml ha^{-1} and Fastac™ at 278 ml ha^{-1}) and adjuvant (Masterlock™ at 292 ml ha^{-1} [WinField United, Arden Hills, MN] and FS Aqua Supreme™ at 175.2 ml ha^{-1} [FS System, Bloomington, IL]) applied together at R3. Reduced row spacing: 50.8 cm compared to 76.2 cm.

2016 - Phosphorus fertilization: MESZ to provide 84 kg of P_2O_5 ha^{-1}, banded before planting. Foliar protection: Fungicide (Priaxor™ at 292 ml ha^{-1} and Quadris Top SBX™ at 511 ml ha^{-1} [Azoxystrobin + Difeconazole; Syngenta, Greensboro, NC]), insecticide (Endigo ZC™ at 292 ml ha^{-1} and Fastac™ at 278 ml ha^{-1}) and adjuvant (Masterlock™ at 292 ml ha^{-1}) applied together at R3. Reduced row spacing: 50.8 cm compared to 76.2 cm.

2017 - Phosphorus fertilization: MES10 or diammonium phosphate (DAP) to provide 84 kg of P_2O_5 ha^{-1}. The DAP was broadcasted before planting, while the MES10 was either banded or broadcasted before planting. Foliar protection: Fungicide (Priaxor™ at 292 ml ha^{-1} and Trivapro™ at 1,000 ml ha^{-1}) and insecticide (Endigo ZC™ at 292 ml ha^{-1} and Fastac™ at 278 ml ha^{-1}) applied together at R3. Reduced row spacing: 50.8 cm compared to 76.2 cm.

2018 - Phosphorus fertilization: MES10 or DAP to provide 84 kg of P_2O_5 ha^{-1}, with DAP broadcasted before planting, while MES10 was either banded or broadcasted before planting. Foliar protection: Fungicide (Priaxor™ at 292 ml ha^{-1} and Trivapro™ at 1,000 ml ha^{-1}) and insecticide (Endigo ZC™ at 292 ml ha^{-1} and Fastac™ at 278 ml ha^{-1}) applied together at R3. Reduced row spacing: 50.8 cm compared to 76.2 cm.

Phosphorus Source, Rate and Placement Soybean

This experiment was conducted for three years (2014-2016) at Champaign, resulting in three site-years. It tested different rates (0, 56, 112 and 168 kg ha^{-1}) of phosphorus using MicroEssentials SZ (MESZ) for all three years, with or without: Titan™ (in 2014) [*Bacillus licheniformis*; Loveland products, Greenville, MS]; Titan™, Zync LS™ [0-0-0-7S-10Zn; WinField United, Arden Hills, MN], or Levesol™ (in 2015); and Levesol™ [20 g kg^{-1} nitrogen and chelating agents; CHS, Inver Grove Heights, MN] or Titan (in 2016). These fertilizers were evaluated using two different application methods (either broadcast or banded). For 2016, a monoammonium phosphate (MAP) with Zync LS™ was also added as a fertilizer mix treatment. All treatment combinations had six replications in 2014 and 2015, and nine replications in 2016. The design was a randomized complete block (RCBD). Only the broadcast versus banded applications of 112 kg ha^{-1} of MESZ were used for meta-analysis, as the other treatments were unique to this project.

Soybean Response to Nitrogen

Conducted from 2013 to 2016, with a design change and expansion from 2013 to 2014, the trial was implemented at five locations (DeKalb, Yorkville, Champaign, Rushville and Harrisburg). Of the locations, Champaign and Harrisburg were held constant over the years, while Rushville and Yorkville were only in 2013 and 2016 respectively, and DeKalb was used from 2013 to 2015, resulting in 13 site-years. The experiment tested the response of soybean to different nitrogen fertilizer sources consisting of urea (45-0-0) and Environmentally Smart Nitrogen (ESN; 44-0-0; Nutrien, Saskatoon, Canada) in 2013, and the other years evaluating urea, ESN, ammonium nitrate (AN) (34-0-0), ammonium sulfate (AMS) (21-0-0-24S) and urea-ammonium nitrate (UAN) (28-0-0). These nitrogen sources were assessed at different application times (before planting, V3, R1 and R3), usually broadcasted. In 2013, a banded before planting treatment was also tested, but was excluded from final data analysis, due to its uniqueness. The fertilizer rate was held constant at 112 kg of N ha^{-1}. The design used was an RCBD, with 2013 being unbalanced, because only one untreated control was used across all treatments and 2014-2016 balanced, with one control for each different time of application. After the statistical analysis, all treatment groups without nitrogen were combined to form an overall control.

Soybean Fertigation

While this experiment was conducted from 2015 to 2018, only the 2015 data was used. It was conducted at Champaign, in a specialized field for fertigation of the University of Illinois farms. The general objective of the trial through the years was to show the behavior of different soybean varieties, with and without fertigation, in different management practices. The specific treatments changed year by year. The trial was a split-plot RCBD, with the fertigation zones being the main blocking factor. While there were different treatments in the overall experiment, only the results from the fungicide plus insecticide application at R3 treatment (Priaxor™: at a rate of 585 ml ha^{-1} and Fastac™: fluxapyroxad and pyraclostrobin at a rate of 278 ml ha^{-1} (BASF, Florham Park, NJ), respectively) was used for data analysis.

Soybean response to Phosphorus Fertilizer Distance

Conducted at Champaign in 2014 and Champaign and Harrisburg in 2015, the trial tested soybean yield and grain quality response to different fertilizer application methods and different distance of the band from the planting row. Phosphorus as MESZ was either broadcasted or banded at 0, 7.6, 15, 22.9, 30.5 or 38.1 cm distance from the planting row to provide a total of 84 kg of P_2O_5 ha^{-1}. Treatments were arranged in an RCBD with eight replications and placement (band vs. broadcast) as the main blocking factor. Data from the broadcasted treatment at 396,000 plants ha^{-1} was evaluated.

Soybean Relay

Conducted in 2016, at three Illinois locations (Yorkville, Champaign and Harrisburg), resulting in three site-years. These trials investigated the yield response of soybean to different placements (broadcasted, banded below the seed, or banded 15 cm from the seed in one or two bands) of a phosphorus fertilizer (MESZ to provide a total of 84 kg of P_2O_5 ha^{-1}), and also with or without a starter of 10-34-0. The experiment was an RCBD with six replications. Data from the broadcast or in the 15 cm one-band phosphorus fertilization without starter treatments were used for analysis.

Statistical analysis

All agronomic management treatments evaluated had respective control plots. Overall, there were 50 site-years assessed, which contributed at least one management factor to the analysis (Appendix A). All site-years were analyzed using the PROC MIXED, PROC UNIVARIATE and PROC GLM procedures of SAS software (Version 9.4, SAS System for Windows, SAS institute Inc., Cary, NC, USA) to generate means and standard deviation values resulting from each management treatment, as well as to check assumptions of normality and homoscedasticity. The outliers were subsequently removed from this original group, leaving at least three replications per treatment.

Data extraction

Each site-year had the experiment type, location and year identified. After the primary statistical analysis, the means, standard deviations and number of observations (replications) of the control (untreated) and the management factor of interest were extracted for the following response variables: yield (metric tons (T) ha^{-1} (0 g kg^{-1} moisture)); protein and oil concentrations (at 130 g kg^{-1} moisture); product and rate used (when appropriate); and application method. Further, other information was extracted to serve as moderators in the model: planting and harvest dates; average temperature (Celsius) and total precipitation (mm) during the period of the crop growth for each site year; soil cation exchange capacity (CEC) (Meq 100 g^{-1}); soil organic matter (OM) (g kg^{-1}); soil pH; and preplant soil phosphorus and potassium levels (mg kg^{-1}).

Quantitative data synthesis

A random effects meta-analysis model was chosen based on the nature of the studies prior to the analysis, and not based on the results from heterogeneity indexes (Borenstein et al., 2009b), using the "meta" package (Schwarzer et al., 2015) in R 3.5.1(R Core Team, 2018). Different management practices were divided into respective sub-groups (i. e. different fertilizer sources per nutrient) prior to the analysis (Table 1). The agronomic management sub-groups that led to significant differences in yield or grain quality were maintained.

For each management practice, heterogeneity values from the meta-analyses were measured using three parameters: 1) The Q test, which tests the hypothesis of having heterogeneity among studies in the meta-analysis; 2) the I^2 value which quantifies how much of the variation observed cannot be explained by the model and; 3) the T^2 which estimates the true variance from the effect size. Based on this analysis, four potential moderators were selected for each management practice based on their impact in the literature and agronomic knowledge. The "metafor" package (*v2.0-0*; Viechtbauer, 2010) was then used to determine the influence of the moderators on the observed heterogeneities. The moderators for each management practice (Table 2) were tested individually. Finally, the models created for each moderator were compared among themselves by the Akaike Information Criteria (AIC), p value and R^2 values (Sakamoto et al., 1988). The model that had a significant p value ($\alpha = 0.05$), a high R^2 value, and a lower AIC value was considered the best model, since it explained most of the observed heterogeneity associated with each management practice.

RESULTS

This study involved five locations, representing a broad cultivation area of Illinois, and seven years of research. The difference in the number of observations for each of the response variables within a management practice (Table 3) was due to abnormal values identified with outlier analyses that were difficult to be normalized. Normally distributed effect values from the data set is a requirement for meta-analyses using the random-effects model (Borenstein et al., 2009a). Therefore, data from site-years that could not be normalized by transformation were not included in the final meta-analysis, and this resulted in a different number of observations per variable within an agronomic management factor.

Nitrogen fertilization

Overall, applying nitrogen to the soybean crop as a broadcasted application prior to planting increased yield by 190 kg ha^{-1} (Table 4). None of the nitrogen fertilizer sources evaluated, (i.e., urea, ESN, ammonium nitrate, ammonium sulfate, urea ammonium nitrate, or Limus urea), was better than the others at increasing yield (Table 5). However, fertilizing with ammonium nitrate tended to increase yield the most (240 kg ha^{-1}), while urea with the urease inhibitor Limus increased yield the least (120 kg ha^{-1}) (data not shown).

The heterogeneity in the model was high for the response of soybean grain yield to nitrogen fertilization, since it has a low p-value in the Q test (<0.0001), not much of the variation from the overall effect is true (0.03), and 92.3% of the variation could not be explained by the model (I^2) (Table 6). Therefore, further analysis was performed using potential moderators of the N fertilizer-yield interaction, including soil cation exchange capacity (CEC), soil organic matter (OM), planting date (PD), and year of the experiment. Of the potential moderators, soil organic matter

(OM) differences explained most of the yield variability in response to N application (Table 7). In regards to grain quality, nitrogen application did not significantly alter the concentration of either protein or oil (Figure 1), and there were no differences between N fertilizer source (Table 5).

The heterogeneity values for the nitrogen fertilization model with the sub-groups for both grain quality aspects were high, with the nitrogen sources having a Q statistics $p < 0.0001$ for both protein and oil (Table 6). Because of this high variability, moderator analysis was performed, using the same potential moderators as for yield (CEC, OM, PD, year). For both grain protein and oil concentrations, planting date acted as a significant moderator to N fertilization, with the highest R^2 value and lowest AIC (Table 7).

Phosphorus fertilization

An increase of 110 kg ha^{-1} in grain yield was observed when at least 84 kg P_2O_5 ha^{-1} of phosphorus fertilization was applied prior to planting soybean (Table 4). There were no differences in yield due to the different P placement strategies, but there were for protein and oil concentrations (Table 5).

The variability in the model was high for the yield response to phosphorus fertilization (Table 6). Thus, a moderator analysis was performed using soil CEC, initial soil P level (P), total precipitation during the growing season (TPr), and the year as the potential moderators. The best moderator of the soybean yield response to phosphorus fertilization was the initial soil P level (P) (R^2=13.5, AIC= 4.6, p-value= <0.01 (Table 7)).

Grain quality was dependent upon P placement strategy (Table 5). When P was applied banded under the seedling row, compared to unfertilized plots, the protein concentration in the grain significantly decreased by 1 g kg^{-1}, and the oil increased by 0.7 g kg^{-1} (Table 9). In contrast, when phosphorus was broadcasted on the surface of the soil, the resulting grain protein and oil concentrations tended to be opposite from those when fertilizer was banded.

The overall variability of grain quality response to P fertilization was high (Table 6), with the broadcasted application sub-group partially explaining the variability (Table 5). Since the fertilizer application sub-groups statistically differed from each other, moderator analysis was done on each placement strategy separately. The same moderators were used as for the yield response to phosphorus fertilization. For banded P fertilization, CEC and year were found to significantly modulate final grain oil and protein levels, while the soil CEC influenced grain protein (lower AIC value and higher R^2), year modulated grain oil concentrations (Table 7). However, for broadcast P placement, year significantly affected grain protein level, while soil CEC affected grain oil concentrations; as both modulator variables had higher R^2 values and lower AICs (Table 7).

Potassium fertilization

Overall, potassium fertilization tended to decrease yield by 30 kg ha^{-1} (Table 4). Because it was the management practice with the lowest number of observations (Table 3), restricted to two years (2014 and 2015), no sub-group analysis was performed. The variability in the yield response to K fertilization was high according to the heterogeneity indicators (Table 6). Thus, an analysis using soil CEC, soil OM, trial location, and soil potassium level (K) as moderators was performed. Soil CEC and location were found to significantly affect the yield response to fertilizer K, with location being the most influential, because of its lower AIC and higher R^2 values (Table 7).

For the grain quality aspects, potassium fertilization only had a modest tendency to increase protein concentration (+0.5 g kg^{-1}) and did not alter oil level (Figure 1). There were, however, only a few data points available for the grain quality parameters for potassium fertilization (Table 3), and as a result, the heterogeneity was high for both parameters (Table 6). Additional analysis was performed to explain this heterogeneity using the same potential moderators as used for yield. While the response to K fertilization in grain protein concentration was moderated primarily by soil CEC (due to a higher R^2 value) none of the moderators tested influenced the response in grain oil concentration.

Row spacing

Reducing space between planting rows from 76 to 51 cm increased yield by 340 kg ha^{-1} (Table 4). To explain the high variability in yield response to this management practice (Table 6), soil CEC, soil OM, total precipitation (TPr) and average temperature (T) of the crop season were selected as potential moderators. Except for average temperature during the crop season (T) all of the other selected moderators influenced the yield response to row spacing, especially soil CEC (R^2 = 60.2) (Table 7).

Reduced row spacing, however, decreased grain protein concentration by 3.1 g kg^{-1} (Table 4) with a corresponding increase in oil level of 0.9 g kg^{-1}. To explain the high heterogeneity, additional analysis using the same potential moderator values as for yield was performed. While no moderator was found to significantly influence the response in grain composition to reduced row spacing, soil CEC accounted for 7% of the variability in protein concentration and 17.8% of the grain oil concentration variability, as shown by the respective R^2 values (Table 7).

Foliar protection

Protecting leaf area with an application of either fungicide or insecticide at R3 increased yield by 150 kg ha^{-1} (Table 4), although there were no yield differences between applying fungicide or insecticide individually versus when they were combined (Table 5). Applying only fungicide, however, tended to increase yield more (180 kg ha^{-1}) then applications of insecticide alone (140 kg ha^{-1}) or the combination of the two (150 kg ha^{-1}) (data not shown). Additionally, analysis by foliar application product was not able to reduce the yield variability (Table 5). Thus, location, soil OM, planting date (PD) and precipitation (TPr) were tested as moderators of the yield response to foliar protectants. Both location and OM resulted in low p-values (0.04 and <0.01, respectively) and similar R^2 values; but since OM had the lower AIC value, it was considered the best moderator of the yield response to foliar protectants (Table 7).

For grain quality, foliar protectant applications at R3 reduced protein concentrations by 1.3 g kg^{-1} (Table 4). In contrast, grain oil concentration was increased by an average of 0.9 g kg^{-1} from an R3 application (Figure 1). The high variability in the grain composition responses to foliar protection (Table 6), had the same moderators as the associated responses in yield (location and OM) (Table 7). For both protein and oil levels, location was determined to be the best moderator of the response to foliar protection, since it had a higher R^2 value (23.5% and 31.4% for protein and oil respectively) (Table 7) and the AIC values between the two moderators were similar.

DISCUSSION

Nitrogen fertilization

Mourtzinis et al. (2018) evaluated the effect of nitrogen application on soybean yields across the United States and concluded that nitrogen fertilizer increased yields by an average of 60 kg ha^{-1} when nitrogen was applied once to the crop, regardless of the application method. The results presented here are similar, in which the application of nitrogen before planting increased yields by 190 kg ha^{-1}. While the production year was the main cause of yield variation in the previous study (Mourtzinis et al. 2018). In the current study, organic matter was the main explanation of yield variation in response to N fertilizer applications. Other multiple-year studies (Lawn and Brun, 1974; Mendes et al., 2008; Cluj-napoca and Turda, 2013; Macák and Candráková, 2013; Bobrecka-Jamro et al., 2018; McCoy et al., 2018) have also found a positive response in soybean yield when nitrogen was applied. Generally, the yield response to N application time varied among the three years, from a 3% increase up to a single 23.5% increase for nitrogen applied immediately prior to planting (Bobrecka-Jamro et al., 2018). According to the authors, the weather was moderate, with warmer temperatures and adequate and equally distributed rainfall over the years, while the soil was low in nitrogen content, with average levels of organic matter. Their data suggest that nitrogen fertilization increased the number of pods per plant, in a directly proportional manner with the nitrogen dose applied and increased the thousand grain weight by 4.8 grams.

A common characteristic among the previous studies that reported increased soybean yields in response to nitrogen mineral fertilization was soil pH between 6.5-7.5 (Lawn and Brun, 1974; Mendes et al., 2008; Cluj-napoca and Turda, 2013; Macák and Candráková, 2013; Bobrecka-Jamro et al., 2018; McCoy et al., 2018). At pH levels close to 7, nitrogen fertilizer as ammonia is a weak base, and therefore is present in its protonated form (ammonium gas), which can be passively absorbed by plants (Souza and Fernandes, 2006). In contrast, other studies that have reported soybean yield decreases in response to nitrogen inputs (Gaydou and Arrivets, 1983; Ferreira et al., 2016; Kaschuk et al., 2016) had more acidic soils (pH approximately 5.0-5.5).

In the current study, the variation in the yield response to nitrogen fertilization was related to the organic matter concentration in the soil, where more organic matter in the soil usually led to greater yields in response to nitrogen fertilization. This relationship, although significant, was weak (R^2 = 16%) indicating that a single moderator factor was not able to account for the variation in soybean yield in response to nitrogen inputs.

Previous studies of soybean response to nitrogen used different N sources, with urea being the most common, and this may have caused the difference in yield response observed in the current study. Therefore, to determine if N fertilizer source was the basis for the variation in the yield response, further analysis of the nitrogen source subgroups (urea, ESN, ammonium nitrate, ammonium sulfate, urea ammonium nitrate and Limus urea) was performed. However, no significant differences between N sources (p-value 0.782) in the yield response to nitrogen were observed (Table 5) and as a result, accounting for the different sources did not decrease the heterogeneity observed (data not shown). Thus, further research is needed that focuses on other environmental factors, such as organic matter and pH in the soil, when studying the effect of nitrogen fertilization on soybean. Furthermore, using nitrogen fertilizer to increase yield in soybean may not always be economical, and the grower and agronomist need to consider the return on investment when deciding whether to fertilize soybean with nitrogen (McCoy et al., 2018).

With regard to changes in the grain protein concentration in response to nitrogen fertilization, several studies agree with the findings presented here that there was no effect of nitrogen fertilization on grain protein concentration (Gaydou and Arrivets, 1983; Macák and Candráková, 2013; Dozet et al., 2016; Ferreira et al., 2016; Moreira et al., 2017). This finding might be explained by the observation that nitrogen from biological fixation is partitioned preferentially to the grain (Hanway and Weber, 1971; Warembourg and Fernandez, 1985; Israel et al., 1987; Pipolo et al., 2015). Moreira et al. (2017) reported that the nitrogen concentration in the grain at R5 was not affected by applications of different sources of foliar nitrogen at the R3 to R4 growth stage, nor was the protein level in the mature grain. In contrast, biological nitrogen fixation during the reproductive growth stages has reportedly contributed to a higher concentration of grain protein (Zapata et al., 1987; Leffel et al., 1992; Purcell et al., 2004).

Increased protein concentration in the grain from nitrogen inputs varies depending on the year and other environmental factors (Bobrecka-Jamro et al. 2018). Grain quality can be highly modified by water availability, as well as the distribution during the crop season (Popovic et al., 2016; Sliwa et al., 2015). In response to three nitrogen fertilization doses (no nitrogen, 35 kg N ha^{-1} and 105 kg N ha^{-1}) in three different water environments (no irrigation; two irrigations of 25 mm at R2 and R4 and two irrigations of 50 mm at the same stages), Basal and Szabó (2018) observed an increase in grain protein concentration from the nitrogen inputs only in the environment with two irrigations of 25 mm at R2 and R4, with the highest nitrogen dose generating a 22 g kg^{-1} greater protein level compared to the control.

In the current study, the variation in grain protein in response to nitrogen fertilization was dependent upon the planting date (Table 7), in which an earlier planting date was associated with a positive response. Since the experiments for this study were conducted in Illinois, which has historically less precipitation in the late months of summer (August and September) (Illinois State

Water Survey, 2019), planting soybean earlier may have prevented seed development and filling from occurring during this drier period, therefore leading to a greater grain protein level.

The oil concentration in the grain was not affected by the nitrogen inputs, similar to previous studies (Gaydou and Arrivets, 1983; Macák and Candráková, 2013; Dozet et al., 2016; Ferreira et al., 2016; Moreira et al., 2017; Bobrecka-Jamro et al., 2018). There was, however, a tendency that nitrogen fertilization led to a slight decrease in grain oil level, which could be explained by the inverse relationship between protein and oil that is often observed (Macák et al., 2010). This inverse relationship was also observed in the explanation of variance, where the most significant moderator was also the planting date (Table 7). Thus, a late planting date led to a greater oil concentration in the grain in response to nitrogen inputs.

Phosphorus fertilization

Preplant phosphorus applications increased soybean yield by 110 kg ha^{-1} (Figure 1) when compared to the plots that were not treated, which yielded 4.86 Mg ha^{-1} on average (Appendix B). Similarly, for soybean grown in Illinois during 2014 and 2015, the addition of 84 kg of P_2O_5 ha^{-1} as MicroEssentials SZ in a band 4-6 inches below the crop row increased yield by 410 kg ha^{-1} (Beyrer, 2018). Yield was previously shown to increase in tandem with the addition of 90, 180 and 360 kg of P_2O_5 ha^{-1}, with a maximum yield increase of 450 kg ha^{-1} (Gaydou & Arrivets 1983). Likewise, Buah et al. (2000) observed a positive yield response to applied phosphorus at every rate tested, and this increase was independent of the on application method (banded or broadcast). This finding is in agreement with the current study, where subgrouping by fertilizer placement was not statistically significant for the yield response (Table 5). Phosphorus level in the soil was the moderator that was best able to account for the variation in the yield response to phosphorus fertilization (Table 8), with a proportional relationship to the yield response. This finding is in contrast to previous findings that soybean planted in soils with low level of phosphorus usually results in a higher yield response to phosphorus fertilizers (Buah et al., 2000).

In contrast to yield, the grain protein and oil concentration responses to P fertilizers were dependent upon the placement (Table 5). When phosphorus was broadcasted, the grain protein level tended to increase by 1 g kg^{-1}, but when P was banded, the grain protein level decreased by 1 g kg^{-1} (Table 9). Studies in Pakistan also observed a maximum increase of 83.4 g kg^{-1} in soybean grain protein with phosphorus applications of up to 120 kg of P_2O_5 ha^{-1} when compared to the control (Abbasi et al., 2010). While Gaydou and Arrivets (1983) also observed grain protein increases due to phosphorus fertilizer nether this study or Abbasi et al. (2010) had details regarding the placement of the phosphorus fertilizer, although it could be assumed that the fertilizer was broadcast. Farmaha et al. (2012), found similar trends in protein yield, in no-till systems where the broadcasted fertilizer led to a higher protein yield than the banded fertilizer for all phosphorus rates tested.

The response in grain oil to phosphorus application was inverse to the protein level, because of the nature of those two characteristics (Macák et al., 2010); oil in the grain was increased by banding phosphorus but tended to decrease when P was broadcasted (Table 8). This trend for grain oil level to decrease with P fertilization was also observed by Gaydou and Arrivets (1983), while Abbasi et al. (2010) observed an increase in grain oil concentration from phosphorus application.

The moderators that contributed to the variation for each grain quality response to P fertilization were the same (CEC and year), but they were reversed for each placement. At this point no previous studies were found examining the linkage between soil CEC or year and grain quality, but it can be inferred that both moderators influenced the quality response to phosphorus fertilization.

Potassium fertilization

Interestingly, the most common fertilization practice for soybean production (potassium fertilization) did not generate any changes in soybean yield or grain quality in this study (Figure 1). The lack of significant response to potassium fertilization could be a consequence of the low number of observations for this management practice (Table 3), which when analyzed in a random model could result in greater between-studies variance (Borenstein et al., 2009c). The yield response to potassium fertilization in the current study tended to be negative, decreasing yield by 30 kg ha^{-1}. A lack of yield response to potassium fertilization was also reported by Yin and Vyn (2002) in Canada with different placements in the fall and the spring, and under different tillage practices. A similar lack of response to potassium fertilization was reported by Buah et al. (2000).

Minimal research has examined the effect of potassium fertilization on soybean grain quality. One report by Gaydou and Arrivets (1983) for a site with a low soil potassium level (highest value was 0.14 meq 100 g^{-1} in the 0-20 cm soil layer), showed that adding potassium fertilizer increased grain oil concentration, while protein decreased. This finding is in contrast with the results from this study, and maybe because the average potassium level in the soils were higher (Appendix C). A study by Abbasi et al. (2010) found no advantage of potassium fertilization for increasing either total grain protein or oil, and Farmaha et al. (2012) observed a negative effect of potassium fertilization on both grain quality parameters.

Row spacing

Planting soybean in a 51 cm between-row spacing instead of a 76 cm spacing increased yield by 340 kg ha^{-1}, the most of any of the management factors studied (Figure 1). Across the United States, the potential for an average 7% yield gain from the adoption of narrow rows has been reported, with the potential to increase yields by 15% in Illinois (Andrade et al., 2019). Similarly a study in Indiana evaluated three row spacings (19, 38 and 76 cm) and observed a yield advantage of narrowing the row spacing when water was not limited (Hanna et al., 2008). In New York, a two-year study that evaluated three different row spacings (19, 38 and 76 cm) and four seedling rates (321, 371, 420 and 469 thousand seeds ha^{-1}) observed an average yield increase of 510 kg ha^{-1} when reducing the row spacing from 76 to 19 cm across all seedling rates (Cox and Cherney, 2011). The greatest yield increase, of 790 kg ha^{-1}, was observed at the lowest seedling rate of 321 thousand seeds ha^{-1} (Cox and Cherney, 2011). In Tennessee, yield increase responses were up to 506 kg ha^{-1} were reported by reducing the row spacing from 76 cm to 38 cm in a droght year (Walker et al., 2010).

The yield increases due to reduced row spacing have also been observed outside the United States. In Argentina, yield increased 798 kg ha^{-1} when the row spacing was reduced from 50 to 25 cm and the number of plants increased by 50%, with a notable increase in seeds per area and no decrease in grain mass (Di Mauro et al., 2019). In the south of Brazil (Rio Grande do Sul), yields from 17 and 34 cm row spacings were greater than from the 51 cm row spacing, and similar to the finding of Di Mauro et al. (2019), grain mass was not affected (Hoffmann et al., 2019). In contrast, Tourino et al. (2002) found no difference in yields from row spacing alterations, regardless of plant density. Similarly, Ferreira et al. (2019) and Moreira et al. (2015) did not observe a yield advantage when the row spacing was reduced in Londrina, Brazil. The row spacing reductions in those studies were from 50 cm to 20 and 30 cm respectively, which may suggest a lower limit to how narrow the row spacing can be for yield increases to be observed, probably due to an increase of plant competition as row width narrows (Çalişkan et al., 2007).

This advantage from narrow rows on soybean yield could be explained by plants being more distributed over the area, having more plant-to-plant space to develop, therefore fostering better plant development. Narrow row spacing have been associated with faster canopy closure (Ball et al., 2000; Silva et al., 2013; Andrade et al., 2019) and greater light interception (Çalişkan et al., 2007; Zhou et al., 2011; Silva et al., 2013), which can lead to more yield at the end of the season.

To explain the variation observed in the yield response to narrow rows (Table 7), total precipitation was considered as a possible moderator, since drought years has been found to decrease the yield response to narrow rows (Hanna et al., 2008; Walker et al., 2010; Cox and Cherney, 2011), especially when the drought occurs during the reproductive stages (Norsworthy and Shipe, 2005). Although total precipitation during the season was a moderator of yield in narrow rows, soil CEC explained more of the model variation (R^2=60.2%) (Table 8). As a result, soils with lower CEC values had a greater yield increase when row spacing was reduced.

Grain protein and oil concentrations exhibited the greatest mean changes in response to row spacing, compared to the other management practices evaluated, with changes of - 3.1 g kg^{-1} and + 0.9 g kg^{-1} respectively (Table 4). While studies in Tennessee (Bellaloui et al., 2014) and in Canada (Al-Tawaha and Seguin, 2006) did not find significant effects of reduced row spacing on soybean protein, the interaction of row spacing and seedling rates has reportedly altered the concentration of grain protein, with the direction of this alteration dependent on the year and the variety (Bellaloui et al., 2014). In Slovenia, a three-year study (2015-2017) also did not observe an effect of reduced row spacing on grain protein concentration (Flajšman et al., 2019). Above-ground plant competition appears to not interfere with seed protein synthesis or concentration in the grain (Umburanas et al., 2018), since it does not affect biological nitrogen fixation, which goes preferentially to the grain (Hanway and Weber, 1971; Warembourg and Fernandez, 1985; Israel et al., 1987; Pipolo et al., 2015). In more tropical climates, decreasing row spacing from 50 to 20 cm between rows increased grain protein by 6 g kg^{-1} (Werner et al., 2017), or tended to increase nitrogen concentration in the grain in response to the reduction in row spacing (Moreira et al., 2017).

When grown in a narrow row spacing, the soybean plant has greater leaf area and more light interception in the early development stages, increasing the production of photosynthesis products available to fill the grain (Ball et al., 2000). However, since the nitrogen in the grain comes primarily from biological nitrogen fixation, and given the fact that reducing row spacing does not enhance this mechanism, the grain was probably filled more with photosynthesis products (such as oil) then with nitrogen. Thus, a decrease in the grain protein concentration was observed (Figure 1).

An increase in grain oil concentration has also been observed in response to reduced row spacing (Flajšman et al., 2019), while other authors did not report any effects of reduced row spacing on grain oil (Al-Tawaha and Seguin, 2006; Bellaloui et al., 2014; Werner et al., 2017). Oil and protein tend to be inversely related in grain crops (Macák et al., 2010), possibly explaining the positive response of oil level to reduced row spacing observed in this current study.

The variation observed for the response in grain quality parameters to reduced row spacing was high (Table 6) and exhibited the largest confidence intervals (Figure 1). While soil CEC for both grain protein and oil levels was selected as the best moderator of the response to reduced row spacing (Table 8), none of the tested moderators were found to have a significant influence.

Foliar protection

The application of foliar protectants (fungicide and/or insecticide) at the R3 growth stage increased soybean yield by 150 kg ha^{-1} (Figure 1). Bender (2015) and Beyrer (2018), also found increased yields in response to foliar protectants applied to soybean in Illinois of 134 and 222 kg ha^{-1}, respectively. A multiple site-year study in Iowa comparing the response to foliar fungicide in small-plot and on farm research also reported increased yields in both trial types in response to a foliar application at the R2-R3 growth stage (Kandel et al., 2018). Another on-farm study with multiple site-years in Ohio reported increased yields due to the fungicide application in 4 out of 10 site-years, and a tendency for increased yields in all the other site-years but one (Ng et al., 2018). The same trial also evaluated the yield response due to the application of insecticides and/or fungicides, and showed no significant response to either insecticide alone, nor the addition of an insecticide to a fungicide application (Ng et al., 2018). Similarly, the current study showed that the sub-groups of different foliar protectant product types (fungicide only, insecticide only, or insecticide and fungicide) were not significantly different from each other and could not explain the variation observed in yield.

When conditions for foliar diseases were not present, fungicide applications did not affect soybean yield, as reported from a multiple site-year study in Iowa (Swoboda and Pedersen, 2009). Other meta-analytical reviews on the impact of fungicides on specific diseases of soybean (i.e., soybean rust (Delaney et al., 2018), target spot (Molina et al., 2019) and sclerotinia stem rot (Willbur et al., 2019)) all concluded that yield gain from foliar applications is greater under conditions with higher disease pressure. Fungicides are used primarily for protecting the leaves and maintaining their green area, thereby maintaining photosynthesis. Photosynthetic assimilates are essential for plant growth and grain storage components, translating to higher yields.

Location, planting date, and total precipitation are environmental factors that can affect the disease pressure of a crop and were considered as moderators to explain the variability in the current study. Soil organic matter, however, was the most significant factor acting as a moderator of the yield response to foliar protectants. Similarly, lower levels of organic matter in the soil is generally considered as being less optimal for growth, and as a result when foliar protectants are applied in combination with this condition, a greater yield response might be expected.

With regard to grain quality, when foliar protectants were applied the grain protein concentration decreased (-1.3 g kg^{-1}), with a corresponding increase in oil (0.9 g kg^{-1}) (Table 4). In a review of 21 studies across 11 states in the United States to assess the variation of soybean grain composition, foliar fungicide and insecticide applications improved grain oil by 3 g kg^{-1} and tended to increase protein by the same amount (Assefa et al., 2019). However, foliar applications had minimal influence on grain composition when pooled with other managements to assess the overall effect of management on soybean grain protein and oil (Assefa et al., 2019). In a multi site-year study in Missouri, fungicide and insecticide applied together decreased protein concentration by 4 g kg^{-1} compared to the control with no foliar protectants applied (Nelson et al. 2010). The grain oil concentration was increased by the fungicide plus insecticide application, as well as by the fungicide by 2 and 1 g kg^{-1} respectively (Nelson et al. 2010). Other study, showed that higher doses of herbicide and insecticide combinations decreased both grain protein and oil levels, while the lowest dose did not affect protein but increased oil concentration (Seddiqui and Ahmed, 2006)

The high heterogeneities observed for both grain quality parameters in response to foliar protection application (Table 6) were primarily explained by the location moderator (R^2 values of 23 and 31% for protein and oil respectively), and secondarily, by soil organic matter level.

CONCLUSIONS

All management practices were geared toward yield increase, with the exception of potassium fertilization. None of the management practices evaluated, however, was able to simultaneously increase soybean yield and grain quality. In general, when yield was increased, grain protein level decreased and oil level increased.

Soybean grain quality has a greater chance to be enhanced by agronomic management in soils with high cation exchange capacity values. However, when the management practice is phosphorus fertilization, the response is dependent on the application method of the fertilizer, specifically whether the fertilizer is broadcast or banded beneath the row.

TABLES AND FIGURE

Table 1. Selected management practices with respective subgroups from soybean management experiments conducted between 2012-2018.

Management Practice	Sub-groups
Nitrogen fertilization	Nitrogen source (urea; ESN†; ammonium nitrate; ammonium sulfate; urea ammonium nitrate; Limus urea‡)
Phosphorus fertilization	Application method (banded or broadcasted)
Foliar protection	Product (fungicide and insecticide; fungicide; insecticide)

†Urea (440 g kg^{-1} nitrogen) with a polymer coating, to control the release of nitrogen from the granule
‡Urea coated with a urease inhibitor to minimize volatilization loss from surface application

Table 2. Variables selected as moderators for each management practice for soybean grown from 2012-2018.

Management Practice	Moderators†
Nitrogen fertilization	CEC; OM; PD; Year
Phosphorus fertilization	CEC; P; TPr; Year
Potassium Fertilization	CEC; K; Location; OM
Row Spacing	CEC; OM; TPr; T
Foliar protection	Location; OM; PD; TPr

† CEC = Cation exchange capacity (Meq 100 g^{-1});
K = Soil potassium level (mg kg^{-1});
Location = city; OM = Soil organic matter level (g kg^{-1});
PD = Planting date;
TPr = Total precipitation (mm);
T = Average temperature (Celsius).

Table 3. Total number of data points for yield, protein and oil in each soybean management practice (nitrogen, phosphorus and potassium fertilizations, reduced row spacing and foliar protection) using 50 site-years of experimentation from 2012-2018.

Management Practice	Variables			**Total**
	Yield	Protein	Oil	
Nitrogen fertilization	59	55	59	173
Phosphorus fertilization	42	33	31	106
Potassium fertilization	6	5	3	14
Row spacing	17	13	9	39
Foliar protection	37	31	23	91
Total	161	137	125	423

Table 4. Soybean yield (Mg ha^{-1}) and grain protein and oil (g kg^{-1}) overall responses and respective 95% confidence interval (C.I.) lower and upper limits for each management practice.

Management Practice	Yield†		Grain concentration‡			
			Protein		Oil	
	Response	C. I.	Response	C. I.	Response	C. I.
	Mg ha^{-1}		---------------------------g kg^{-1}-------------------------			
Nitrogen fertilization	0.19	[0.15; 0.23]	0.1	[-0.5; 0.7]	-0.1	[-0.4; 0.3]
Phosphorus fertilization	0.11	[0.06; 0.16]	-0.6	[-1.1; -0.1]	0.5	[0.2; 0.8]
Potassium fertilization	-0.03	[-0.11; 0.05]	0.5	[-1.7; 2.7]	-0.1	[-1; 0.7]
Row spacing	0.34	[0.22; 0.45]	-3.1	[-5.9; -0.2]	0.9	[0.3; 1.4]
Foliar protection	0.15	[0.12; 0.19]	-1.3	[-1.8; -0.8]	0.9	[0.5; 1.4]

†Yield values presented with 0 g kg^{-1} of moisture
‡Grain concentration presented with 130 g kg^{-1} of moisture

Table 5. Between sub-group differences p-value, for nitrogen (N) and phosphorus (P) fertilization and foliar protection, when each specific subgroup was added to the model for soybean responses to various management practices.

Management Practice	Sub-group	Variables		
		Yield	Protein	Oil
N fertilization	Source†	0.782	0.199	0.462
P fertilization	Placement‡	0.356	0.021*	0.003*
Foliar protection	Product§	0.743	0.415	0.701

† Different sources were: urea, ESN, AN, AMS, UAN and Limus urea.

‡ Different placements were: broadcast on the surface or banded 5 cm to the side and under the row.

§ Different products were: fungicide only, insecticide only or both.

* Significant difference between sub-groups at p = 0.05.

Table 6. Q statistic p-value, estimate of the variance of the true effect (T^2) and the percentage of excess dispersion to the total dispersion (I^2) values for each management practice tested (nitrogen, phosphorus and potassium fertilization; reduced row spacing and foliar protection), used to asses heterogeneity for yield and protein and oil grain concentration of soybean.

Management Practice	Yield	Grain Concentration	
		Protein	Oil
Nitrogen fertilization	$p < 0.0001$ $T^2 = 0.03$ $I^2 = 92.3\%$	$p < 0.0001$ $T^2 = 0.04$ $I^2 = 89.5\%$	$p < 0.0001$ $T^2 = 0.02$ $I^2 = 87.5\%$
Phosphorus fertilization	$p = 0$ $T^2 = 0.03$ $I^2 = 99.2\%$	$p = 0$ $T^2 = 0.02$ $I^2 = 98.4\%$	$p = 0$ $T^2 = 0.006$ $I^2 =98.4\%$
Potassium fertilization	$p < 0.0001$ $T^2 = 0.01$ $I^2 = 96.6\%$	$p < 0.0001$ $T^2 = 0.06$ $I^2 = 98.1\%$	$p = 0.0005$ $T^2 = 0.007$ $I^2 =86.8\%$
Row spacing	$p = 0$ $T^2 = 0.06$ $I^2 = 99.9\%$	$p = 0$ $T^2 = 0.27$ $I^2 = 100\%$	$p < 0.0001$ $T^2 = 0.007$ $I^2 =98.8\%$
Foliar protection	$p = 0$ $T^2 = 0.01$ $I^2 = 98.6\%$	$p = 0$ $T^2 = 0.02$ $I^2 = 98.7\%$	$p = 0$ $T^2 = 0.01$ $I^2 =99.3\%$

Table 7. The p-value for each moderator, Akaike information criterion (AIC), and R^2 values for the response in yield and grain protein and oil concentration to each management factor with non-significant subgroup (nitrogen fertilization; potassium fertilization; reduced row spacing; and foliar protection).

					Grain concentration					
Manage-ment	Mode-rator†	Yield			Protein			Oil		
		p‡	AIC	R^2	p	AIC	R^2	p	AIC	R^2
Nitrogen	CEC	0.26	-23.2	0.4	0.26	7.3	0.8	0.20	-48.5	2.1
	OM	<0.01	-32.3	16.5	0.38	7.7	0	0.77	-47.1	0
	PD	0.21	-23.5	0.7	0.03	4.0	8.8	0.03	-51.5	5.9
	Year	0.23	-23.4	0.4	0.65	8.4	0	0.32	-47.9	0
Potassium	CEC	<0.01	-2.5	57.5	0.20	8.0	26.3	0.38	4.1	0
	K	0.95	1.7	0	0.42	7.3	0	0.40	4.1	0
	L	<0.01	0.1	77.8	0.84	7.8	0	0.76	4.4	0
	OM	0.15	>-0.1	18.7	0.45	7.3	0	0.58	4.3	0
Row spacing	CEC	<0.01	-2.6	60.2	0.17	32.5	7.0	0.12	-10.3	17.8
	OM	<0.01	0.8	50.2	0.58	34.0	0	0.23	-9.5	6.1
	TPr	0.03	8.2	18.6	0.29	33.2	1.2	0.23	-9.5	7.0
	T	0.43	11.6	0	0.89	34.3	0	0.14	-10.2	14.2
Foliar protection	L	0.04	-31.8	15.1	0.01	40.5	23.5	<0.01	16.2	31.4
	OM	<0.01	-40.2	16.4	0.01	40.0	16.5	<0.01	15.6	23.5
	PD	0.39	-36.2	0	0.14	44.3	3.9	0.14	19.7	5.5
	TPr	0.76	-35.5	0	0.59	46.1	0	0.56	21.3	0

† CEC = Cation exchange capacity (Meq 100 g^{-1}); K = Soil potassium level (mg kg^{-1}); L = Location (city); OM = Soil organic matter level (g kg^{-1}); PD = Planting date; TPr = Total precipitation (mm); T = Average temperature (Celsius).
‡ p = p-value

Table 8. The p value for each, Akaike information criterion (AIC), and R^2 values for soybean yield response to phosphorus fertilization, accounting for the sub-group (banded and broadcasted) in the grain quality (protein and oil concentration) responses.

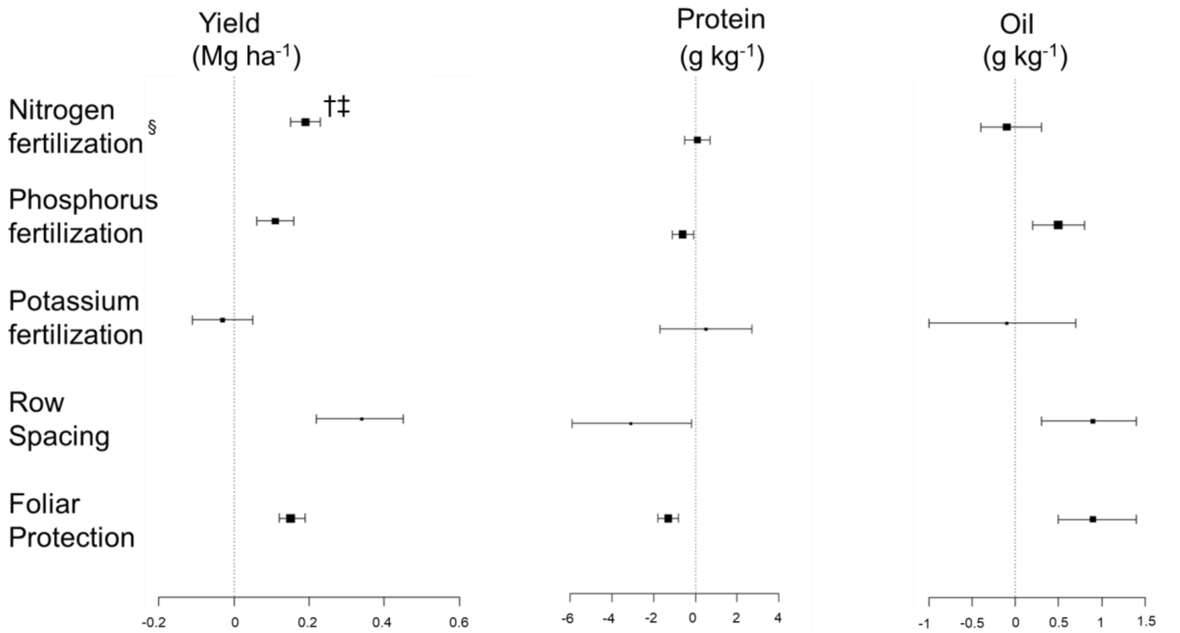
Response	Moderators†											
	CEC			P			TPr			Year		
	p‡	AIC	R^2	p	AIC	R^2	p	AIC	R^2	p	AIC	R^2
Yield	0.49	10.7	0	<0.01	4.6	13.5	0.60	10.9	0	0.22	9.7	1.2
Protein	Banded											
	0.04	13.0	12.2	0.47	45.4	0	0.58	46.6	0	0.05	43.5	10.1
	Broadcasted											
	0.42	6.9	0	0.75	7.4	0	0.46	6.9	0	0.22	6.1	6.6
Oil	Banded											
	0.04	11.6	13.3	0.43	14.6	0	0.42	14.6	0	0.03	11.1	16.0
	Broadcasted											
	0.02	-9.2	41.3	0.70	-5.0	0	0.39	-5.6	0	0.26	-6.0	1.0

† CEC = Cation exchange capacity (Meq $100g^{-1}$); P = Soil; phosphorus level (mg kg^{-1}); TPr = Total precipitation (mm).

‡ p = p-value

Table 9. Soybean grain quality components (protein and oil concentrations) overall responses and respective 95% Confidence Interval (C.I.) lower and upper limits for each phosphorus fertilizer placement strategy.

Phosphorus placement	Protein		Oil	
	Response	C. I.	Response	C. I.
	-------------------------	g kg^{-1}	--------------------------	
Banded	-1.0	[-1.6;-0.5]	+0.7	[0.4; 1.1]
Broadcasted	+1.0	[-0.6;+2.6]	-0.2	[-0.6; 0.3]



† Bigger boxes have more weight over the overall effect (not shown).
‡ Lines represent the upper and lower limits of the 95% Confidence Interval.
§Represented as the difference between experimental and control groups, respectively being: fertilized and unfertilized for fertilization factors; 51 and 76 cm for row spacing, and; applied and unapplied for foliar protection.

Figure 1. Forest plot of the overall effects of management practices (nitrogen, phosphorus and potassium fertilizations; row spacing and foliar protection) on soybean yield, grain protein and oil concentrations in comparison with the respective untreated controls.

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APPENDIX: SUPPLEMENTAL TABLES

Table 10. Included experiments, years and location of trials used in the meta-analysis. The productivity parameters measured and the agronomic management practices examined in each trial are noted with check marks.

		Productivity Parameters			Agronomic Management				
Year	Location	Yield (T ha^{-1})	Protein (g kg^{-1})	Oil (g kg^{-1})	Fertility N	Fertility P	Fertility K	Reduced row spacing	Foliar protection
Management Yield Potential									
2016	Champaign	✓	✓	✓					
	Yorkville	✓	✓	✓					
2017	Champaign	✓	✓	✓					
	Harrisburg		✓	✓					
	Yorkville	✓	✓	✓		✓			✓
2018	Champaign	✓							
	Harrisburg	✓							
	Yorkville	✓							
Omission Plots									
2012	Champaign	✓							
	DeKalb	✓	✓	✓					
	Harrisburg	✓	✓	✓		✓		✓	✓
	Rushville		✓						
2013	Champaign	✓	✓	✓					
	DeKalb		✓			✓		✓	✓
	Harrisburg	✓							
	Rushville	✓							
2014	Champaign	✓	✓						
	DeKalb	✓	✓	✓		✓	✓	✓	✓
	Harrisburg	✓	✓	✓					
2015	Champaign	✓	✓						
	DeKalb	✓	✓	✓		✓	✓	✓	✓
	Harrisburg	✓							
2016	Champaign	✓	✓	✓					
	Harrisburg	✓	✓			✓		✓	✓
	Yorkville	✓	✓	✓					
2017	Champaign	✓		✓		✓		✓	✓
2018	Champaign	✓				✓		✓	✓

Table 10. (continued).

Year	Location	Productivity Parameters			Contribution to the review				
		Yield (T ha^{-1})	Protein (g kg^{-1})	Oil (g kg^{-1})	Fertility N	Fertility P	Fertility K	Reduced row spacing	Foliar protection
Phosphorus Source, Rate and Placement									
2014	Champaign	✓	✓	✓					
2015	Champaign	✓	✓	✓		✓			
2016	Champaign	✓	✓	✓					
Soybean Response to Nitrogen									
2013	Champaign	✓	✓	✓					
	DeKalb	✓	✓	✓					
	Harrisburg	✓	✓	✓	✓				
	Rushville	✓	✓	✓					
2014	Champaign	✓		✓					
	DeKalb	✓	✓	✓					
	Harrisburg	✓	✓	✓					
2015	Champaign	✓	✓	✓					
	DeKalb	✓	✓	✓	✓				
	Harrisburg	✓	✓	✓					
2016	Champaign	✓	✓	✓					
	Yorkville	✓	✓	✓					
	Harrisburg	✓	✓	✓					
Soybean Fertigation									
2015	Champaign	✓	✓	✓					✓
Soybean Response to Fertilizer Distance									
2014	Champaign	✓	✓	✓					
2015	Champaign	✓	✓	✓		✓			
	Harrisburg	✓	✓	✓					
Soybean Relay									
2016	Champaign	✓	✓	✓		✓			

Table 11. Average values of yield (Mg ha^{-1}) and grain protein and oil concentration (g kg^{-1}) for the untreated control plots for each management practice.

Management Practice	Yield†	Grain‡	
		Protein	Oil
	Mg ha^{-1}	g kg^{-1}	g kg^{-1}
Nitrogen fertilization	4.16	346.7	191.4
Phosphorus fertilization	4.86	349.3	190.7
Potassium fertilization	4.74	347.6	185.8
Row spacing	4.60	352.1	188.9
Foliar protection	4.63	353.7	189.2

†Yield values presented with 0 g kg^{-1} of moisture
‡Grain concentration presented with 130 g kg^{-1} of moisture

Table 12. Average preplant values of soil organic matter (OM), cation exchange capacity (CEC), pH, phosphorus (P), and potassium (K) levels by location.

Location	OM	CEC	pH	P	K
	g kg^{-1}	Meq/100g		------- mg kg^{-1}------	
DeKalb	43	21.2	6.5	26	132
Yorkville	56	26.0	6.2	39	206
Champaign	36	19.6	6.0	32	133
Rushville	20	10.9	5.8	35	188
Harrisburg	28	18.4	6.3	32	171